

Transiting Exoplanet Survey Satellite (SMEX mission in Phase A)

Presented by:

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MIT Kavli Institute

Missions for Exoplanets: 2010-2020
Pasadena, California
21 April 2009



TESS Science Team

Pink:
Kepler & JWST Team

Name	Institution	TESS Responsibility
G. R. Ricker	MIT	Principal Investigator
D. W. Latham	CfA	Chief Mission Scientist; Follow-up science
K. A. Ennico	NASA Ames	NASA Project Scientist
R. Vanderspek	MIT	Payload Project Scientist; SOC Manager
G. Bakos	CfA	Transit detection algorithms
T.M. Brown	Los Cumbres	LCOGT spectroscopic & photometric follow-up
A.J. Burgasser	MIT	Target selection; MIT IR follow-up
D. Charbonneau	CfA	Follow-up observing; Interpretation of TESS candidates
M. Clampin	NASA GSFC	JWST spectroscopic follow-up
L.D. Deming	NASA GSFC	JWST spectroscopic follow-up
J. P. Doty	Espace/ MIT	Payload systems engineer; SOC staff
E.W. Dunham	Lowell Observatory	Optical Design; Camera ground testing; SOFIA followup
J. L. Elliot	MIT	MIT follow-up photometry
G. P. Laughlin	UC-Santa Cruz	Observational transit photometry; E/PO Liaison
M.J. Holman	CfA	CfA photometric follow-up (Mt. Hopkins)
S. Ida	Tokyo Tech	Theory of exoplanets
J.M. Jenkins	SETI	Adaptation of Kepler transit detection methods
J.G. Jernigan	Espace	Transit algorithms; SEO Serendipitous Science
N. Kawai	Tokyo Tech	Ground followup
J.J. Lissauer	NASA Ames	Theory of exoplanets
F. Martel	Espace/ MIT	Ground station network manager
D.D. Sasselov	CfA	Modeling of super-Earths; HARPS-N facility
R. H. Schingler	NASA Ames	Partnership and Public Participation Manager
S. Seager	MIT	Exoplanet modeling; SC Lead; JWST follow-up
G. Torres	CfA	CfA spectroscopic follow-up
S. Udry	Geneva Observatory	Radial velocity follow-up with Coralie and HARPS-S
J.S. Villasenor	MIT	CCD Scientist; SOC staff
J. N. Winn	MIT	Light curve analysis; MIT follow-up photometry
S.P. Worden	NASA Ames	Strategic NASA linkage; TESS GI liaison



Outline

- Science Goals
- Discovery Space
- Mission Design
- Instrumentation
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- Followup Programs
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TESS Addresses NASA'S Strategic Goals

2006 NASA Strategic Plan, p. 12:

- “Conduct advanced telescope searches for earth-like planets and other habitable environments around **nearby stars**”

2008 NSF-NASA Exoplanet Task Force, pp. 33-34:

- Value mission that provides “...**wide-shallow** equivalent of Kepler using a small satellite with a very large instantaneous field of view.”
- Search the entire sky for transiting planets around “...the **brightest possible host stars**, down to at least 10th magnitude.”



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TESS Science Goals

All Sky Survey of Bright Stars

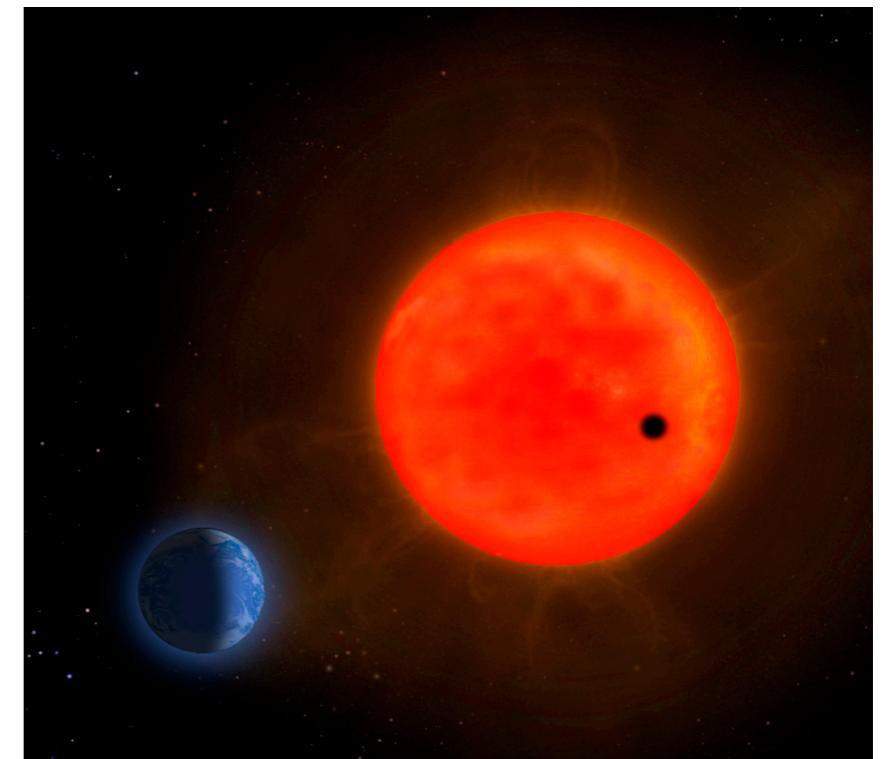
- F, G, K dwarf stars: 4.5 to 13.5 magnitude
- M stars: the brightest ones known within 100 light-years
- 2,500,000 stars in two years
- Discover 1000+ new exoplanets
 - Locate superEarths and Earth-sized planets

Provide IR-Bright Targets for JWST

- Comparative planetology
- Atmospheric studies

TESS Legacy

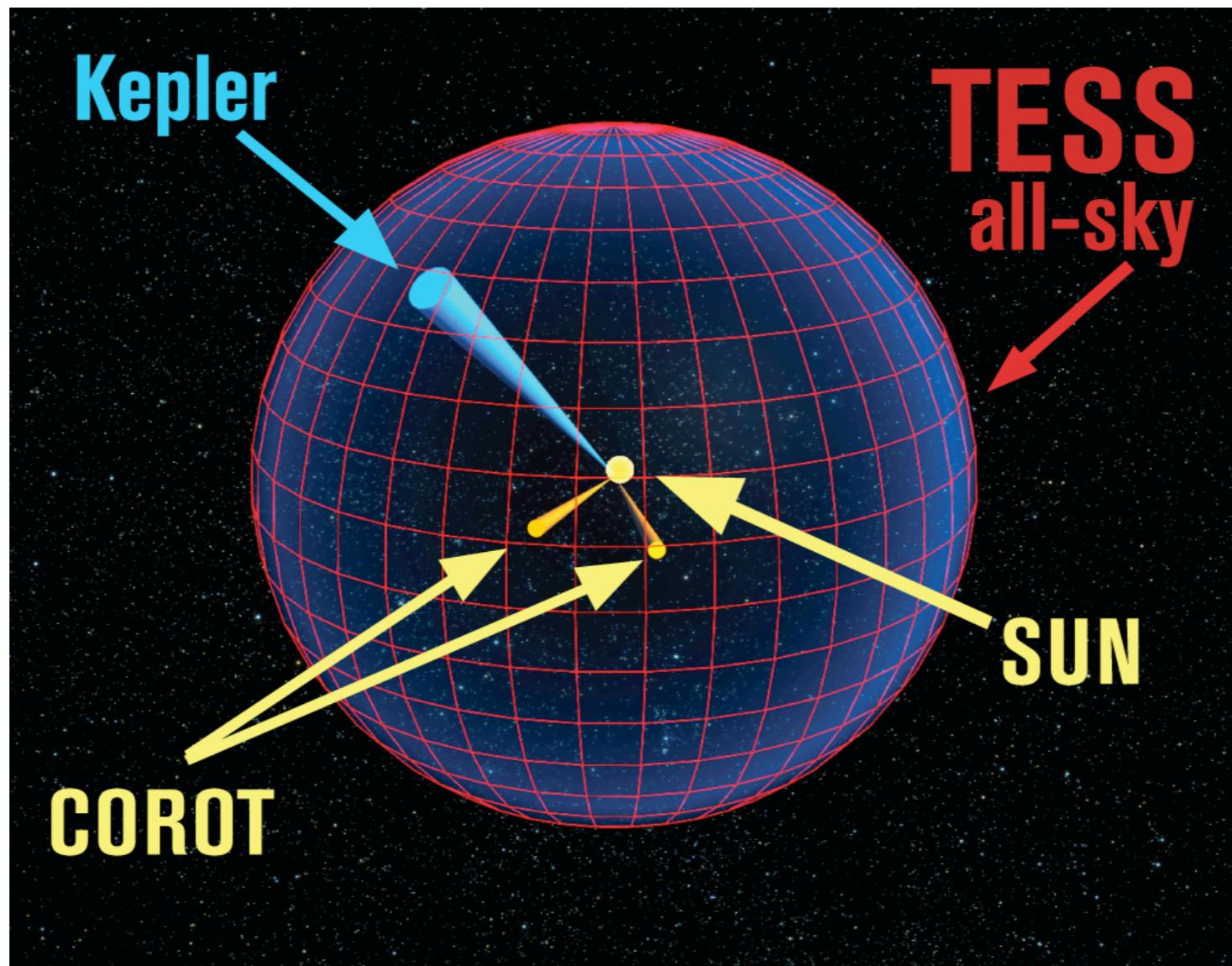
- Will discover the nearest and brightest transiting systems
- Will establish the best targets for follow-up studies by other missions for decades to come





TESS and Kepler

- TESS is Complementary to Kepler
 - “Broad-shallow” vs “Narrow-Deep”
 - Brighter sample: 10x to 20x brighter stars



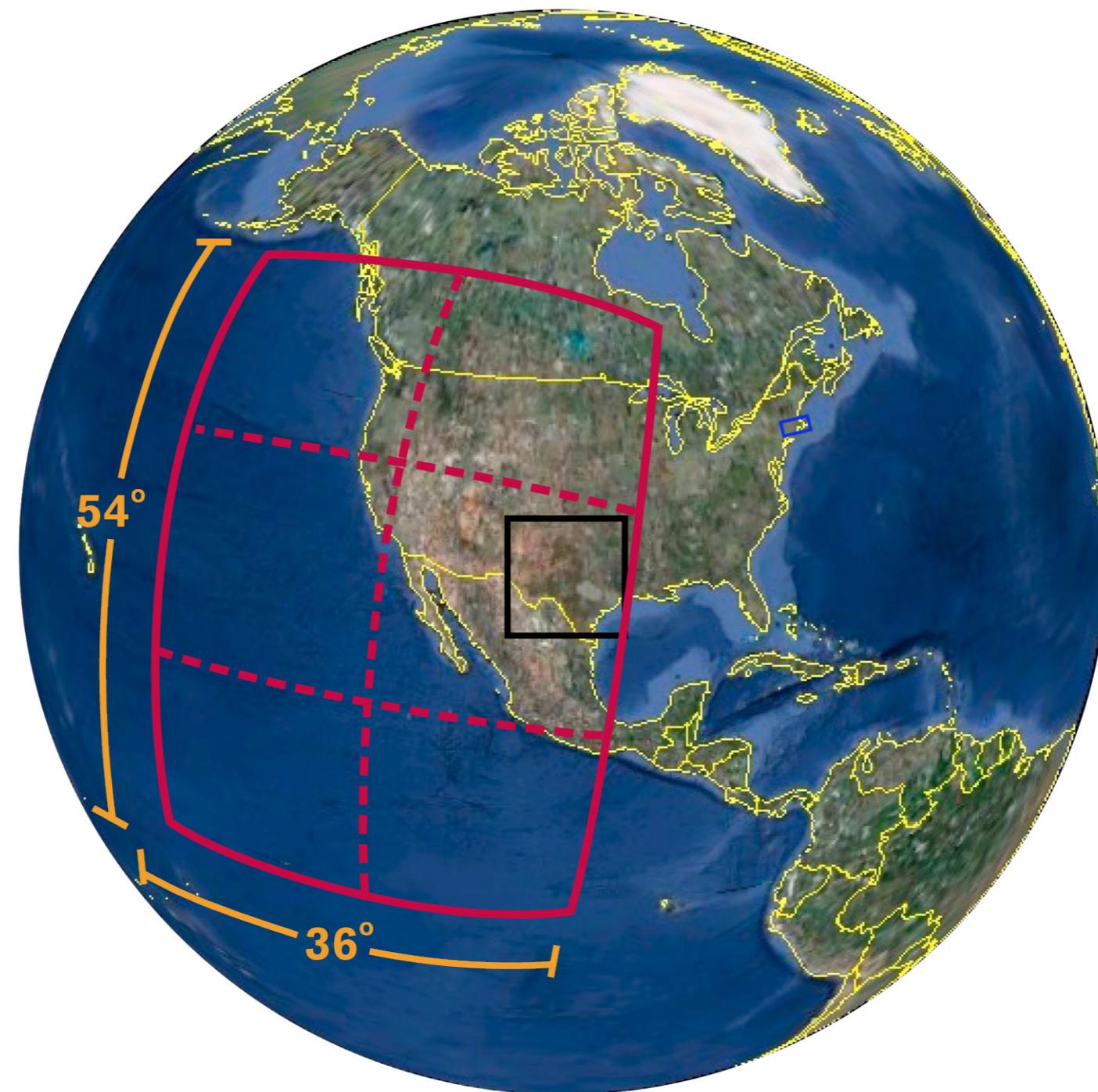


Corot and Kepler Fields of View



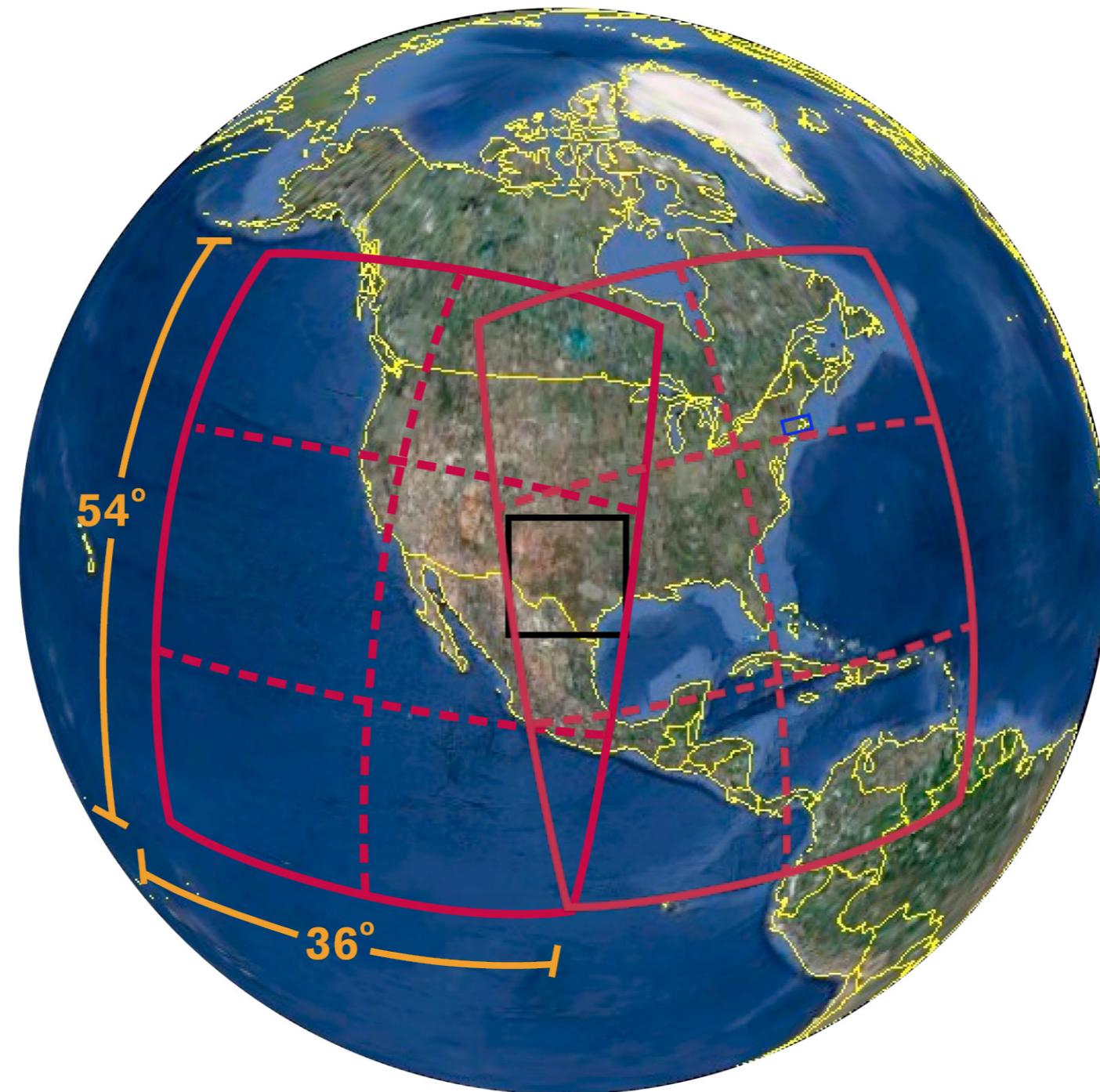


TESS Observation 1 Field of View



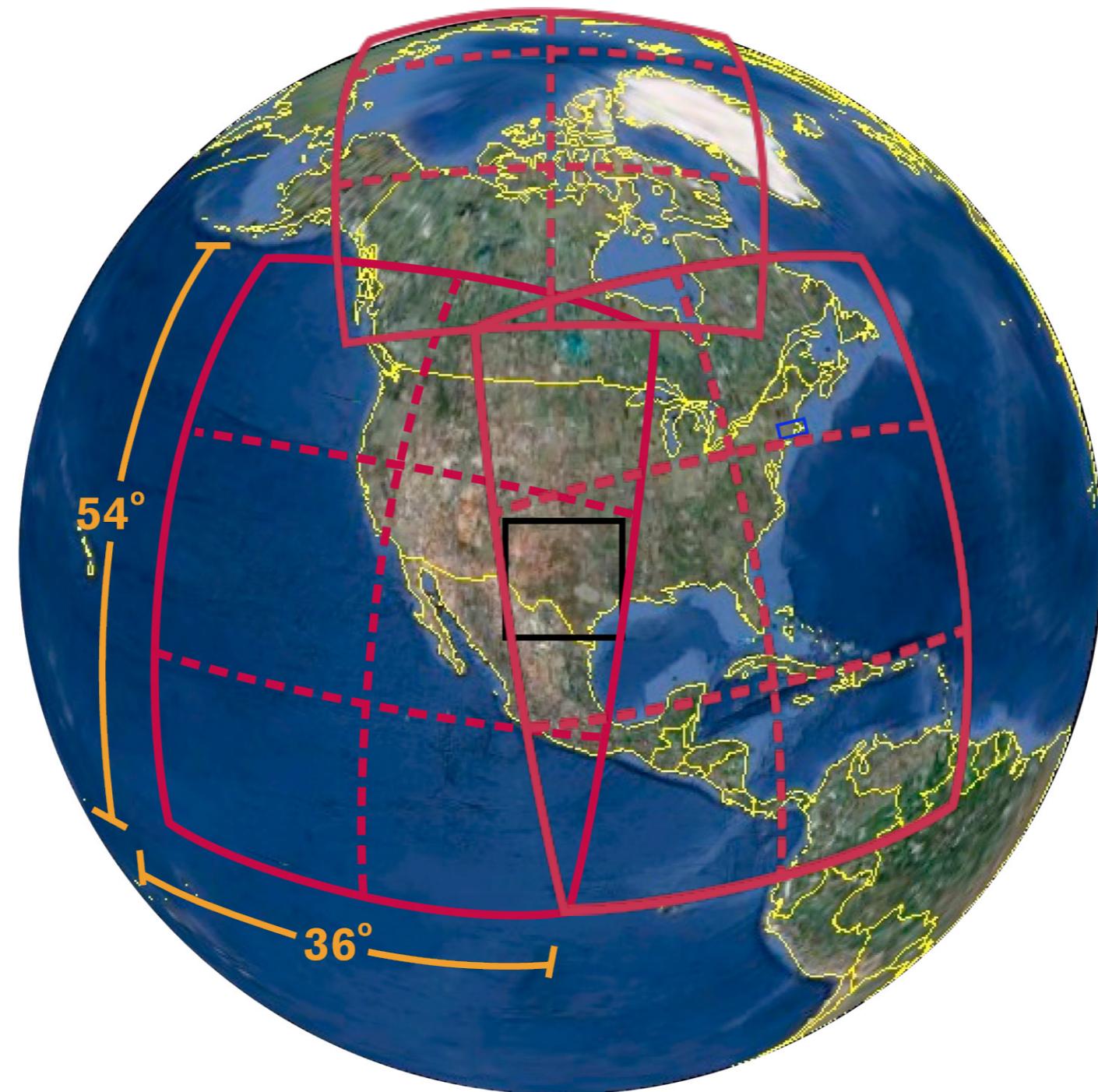


TESS Observations 1 and 2 Fields of View





TESS Total Field of View per Orbit



~6000 deg² Covered Each Orbit



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Discovery Space for Transit Surveys

Q: Why do a satellite-based survey?

A: Greatly improved photometric precision for small amplitude transits of bright stars

- ➡ Freedom from earth's atmosphere effects
 - ▶ Scintillation
 - ▶ Extinction

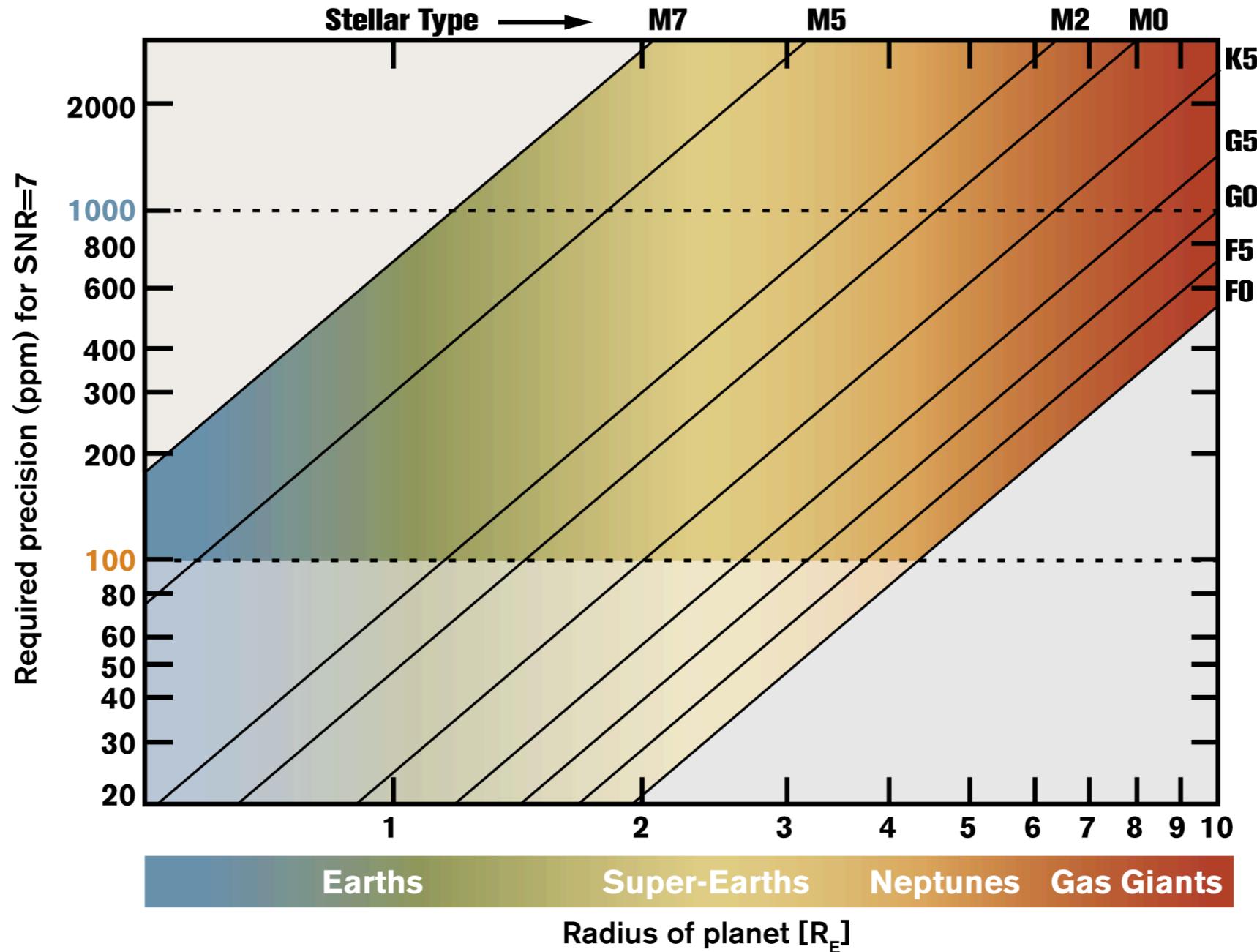
Impractical limits for ~100ppm from ground for even a 50,000 star survey:

17,000 telescope-yrs (Brown LCOGT);

100,000 telescope-yrs (Latham MHO; 1m-class telescope)

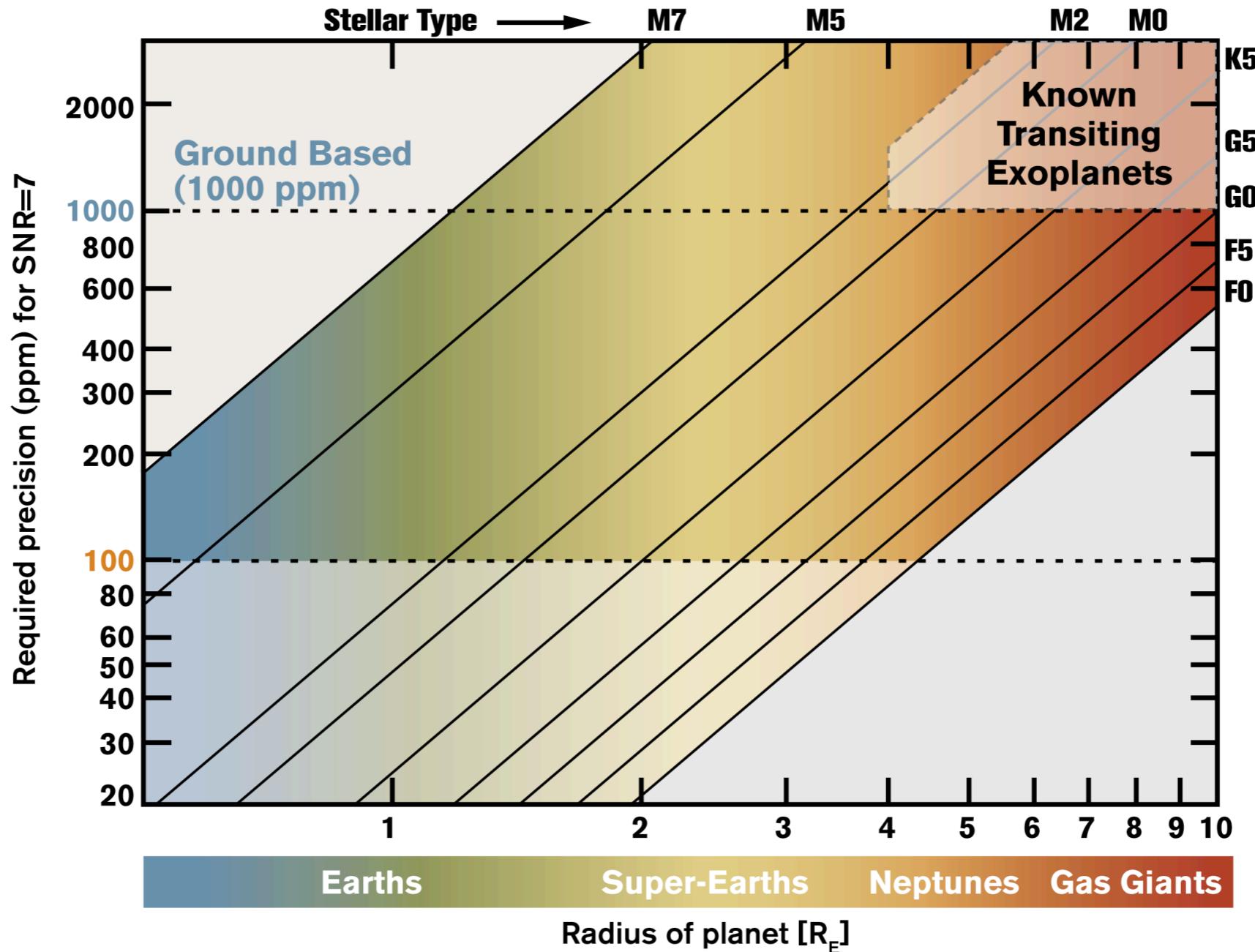


TESS Discovery Space



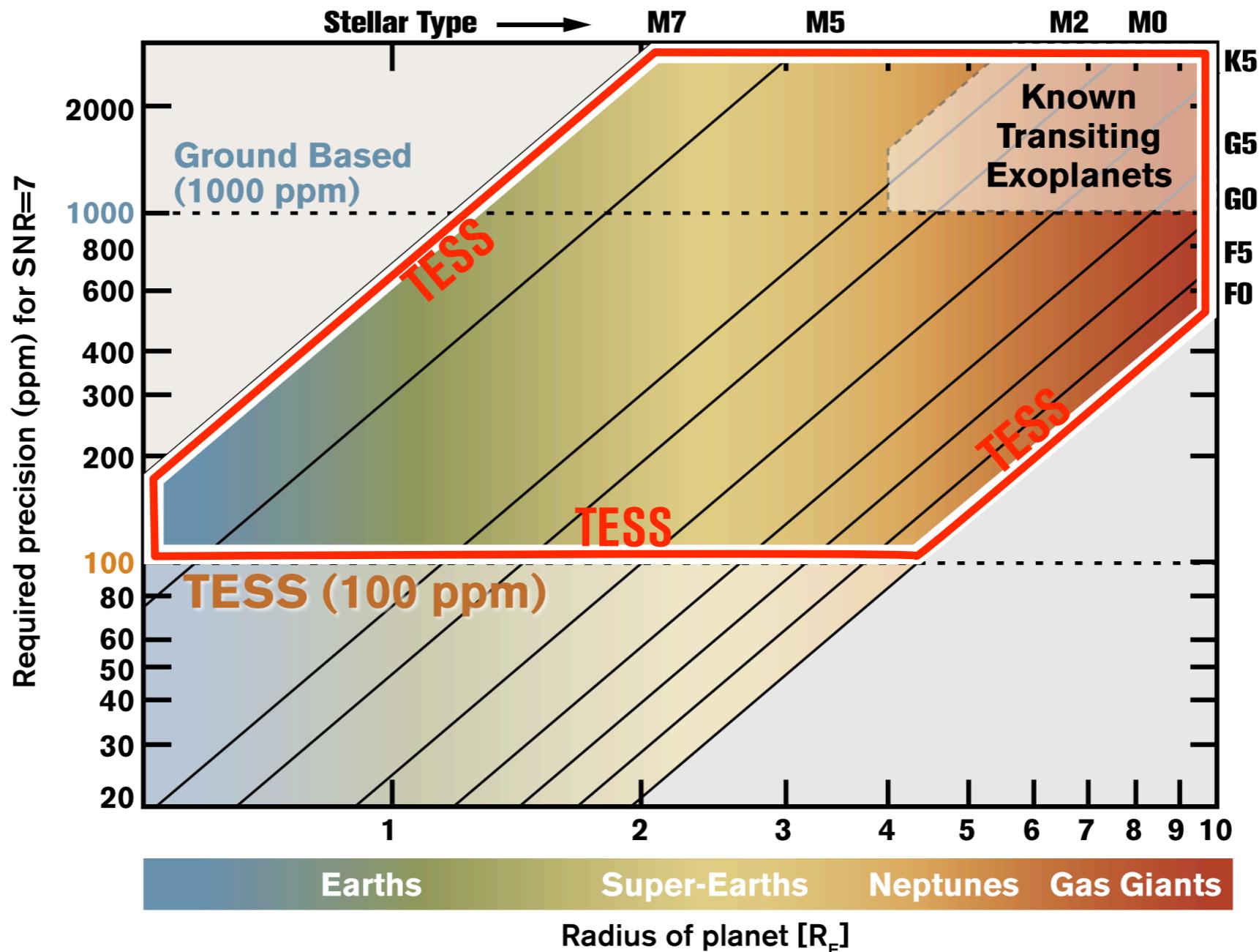


TESS Discovery Space





TESS Discovery Space



TESS Finds Earth-Sized Planets to Gas Giants



TESS Yield Calculation Model

Question: How many transiting planets will TESS detect?

- Function of planetary radius, orbital distance, stellar type

Key Inputs:

- Planet: radius r and orbital distance a
- Star: luminosity L , mass M , radius R , number density n
- Probability for each star-planet-orbit combination, $\text{Prob}(r, a', L)$
- TESS instrument: effective area, bandpass, limiting precision
- TESS survey: input catalog, duty cycle, campaign duration



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TESS Yield Calculation Model, Continued

Overview:

1. For each star-planet-orbit combination,
 - Find # of stars offering $\text{SNR} > 7$
 - Multiply by geometric transit probability (assumes randomly-oriented circular orbits)

2. Multiply by an assumed $\text{Prob}(r, a', L)$
 - Based on data for gas giants and theoretical expectations

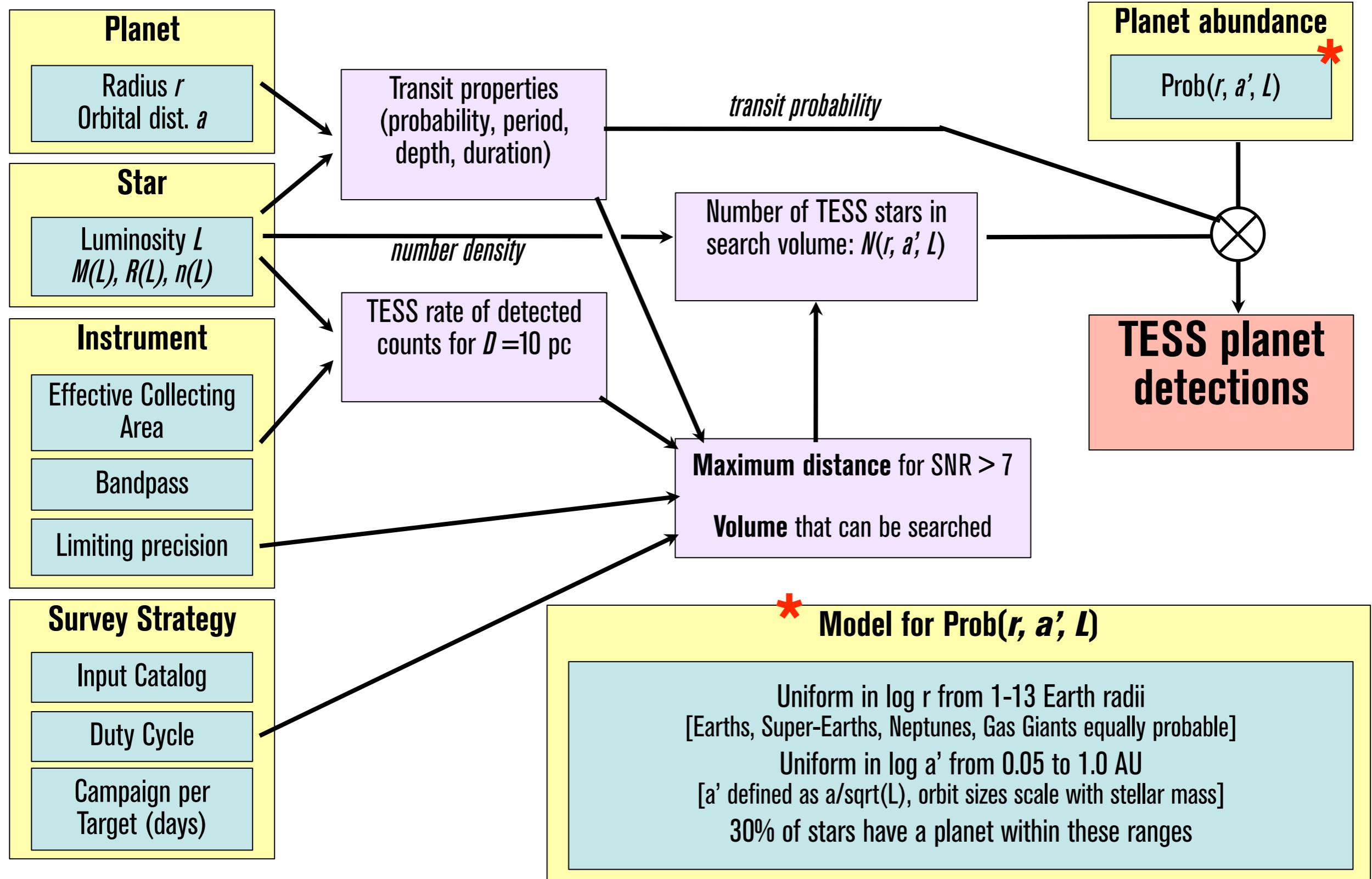


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Calculation Flow Diagram





Example of a TESS Yield Table: Earth-sized* Planets for 100 ppm

Spectral Type	# Stars	Assumed Planet Fraction	# Transit Detections	I _{mag} Range		Distance (pc)		Mean ppm Drop	Mean Transit Dur/Period	Mean Period (days)
				Min	Max	Min	Max			
G1	1,684,609	0.075	0							
G8	291,070	0.075	0							
K2.5	113,248	0.075	0							
K4	35,019	0.075	0							
K7	18,011	0.075	1	8.73	8.73	24.3	24.3	529	0.038	1.71
M0.8	5,155	0.075	9	9.52	11.11	25.3	52.6	688	0.048	1.09
M1.9	2,299	0.075	8	9.72	11.23	18.8	37.6	854	0.045	1.35
M2.9	643	0.075	3	10.24	11.03	17.1	24.6	946	0.042	1.69
M3.7	165	0.075	1	10.82	10.82	15.8	15.8	1055	0.040	2.10
M4.4	32	0.075	0							
M5	5	0.075	0							
M5.6	2	0.075	0							
Total			22							

* $1.0 R_E < R < 1.75 R_E$

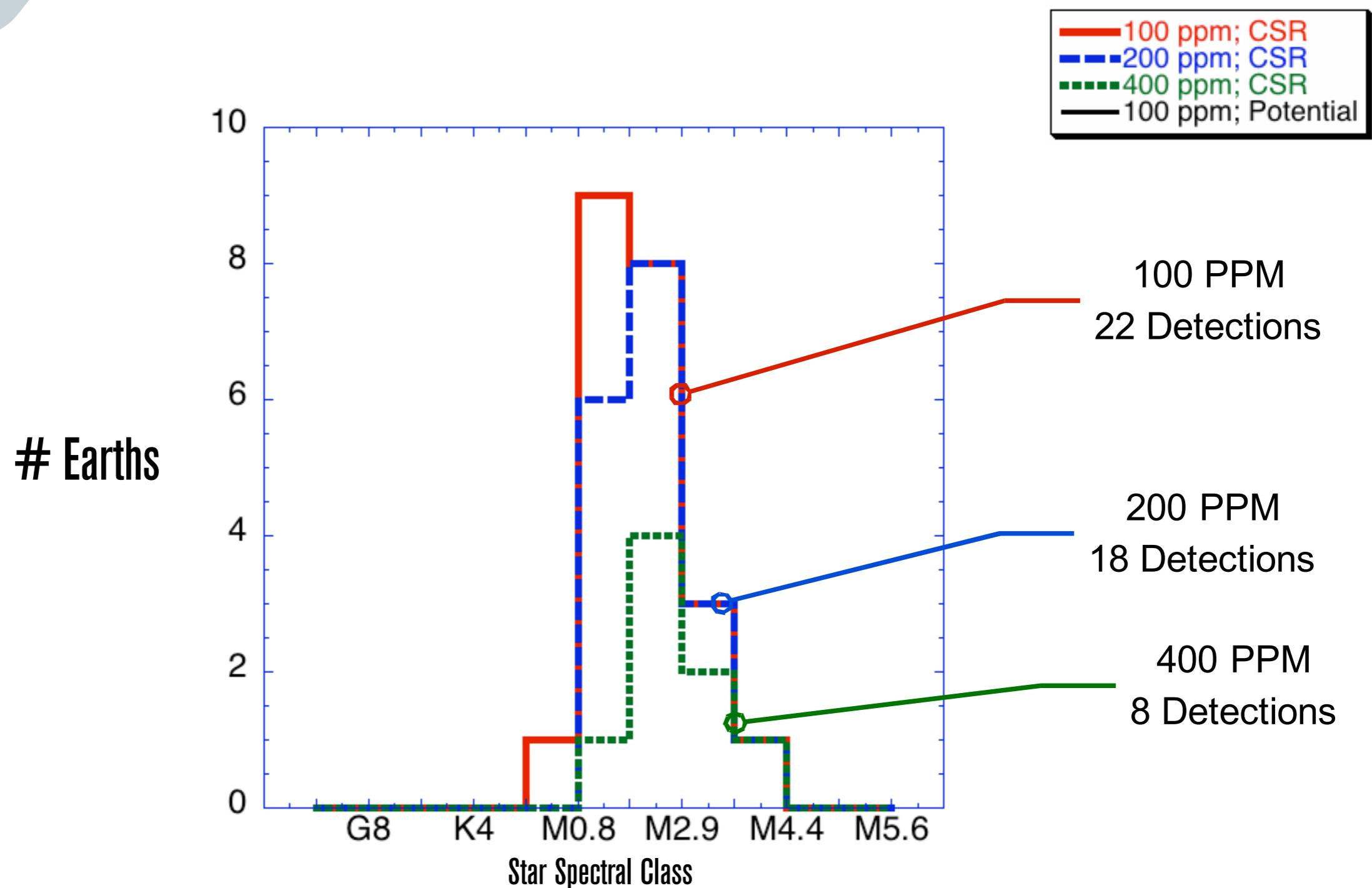
Additional consideration: Recent results from Geneva Observatory HARPS radial velocity studies –

C. Lovis, M. Mayor, F. Bouchy, F. Pepe, D. Queloz, S. Udry, W. Benz and C. Mordasini (2008). “Towards the characterization of the hot Neptune/super-Earth population around nearby bright stars.” Proceedings of the International Astronomical Union, 4 , pp 502-505

→ Low mass planets seem to be ~3 x as common as we assumed in our original modelling



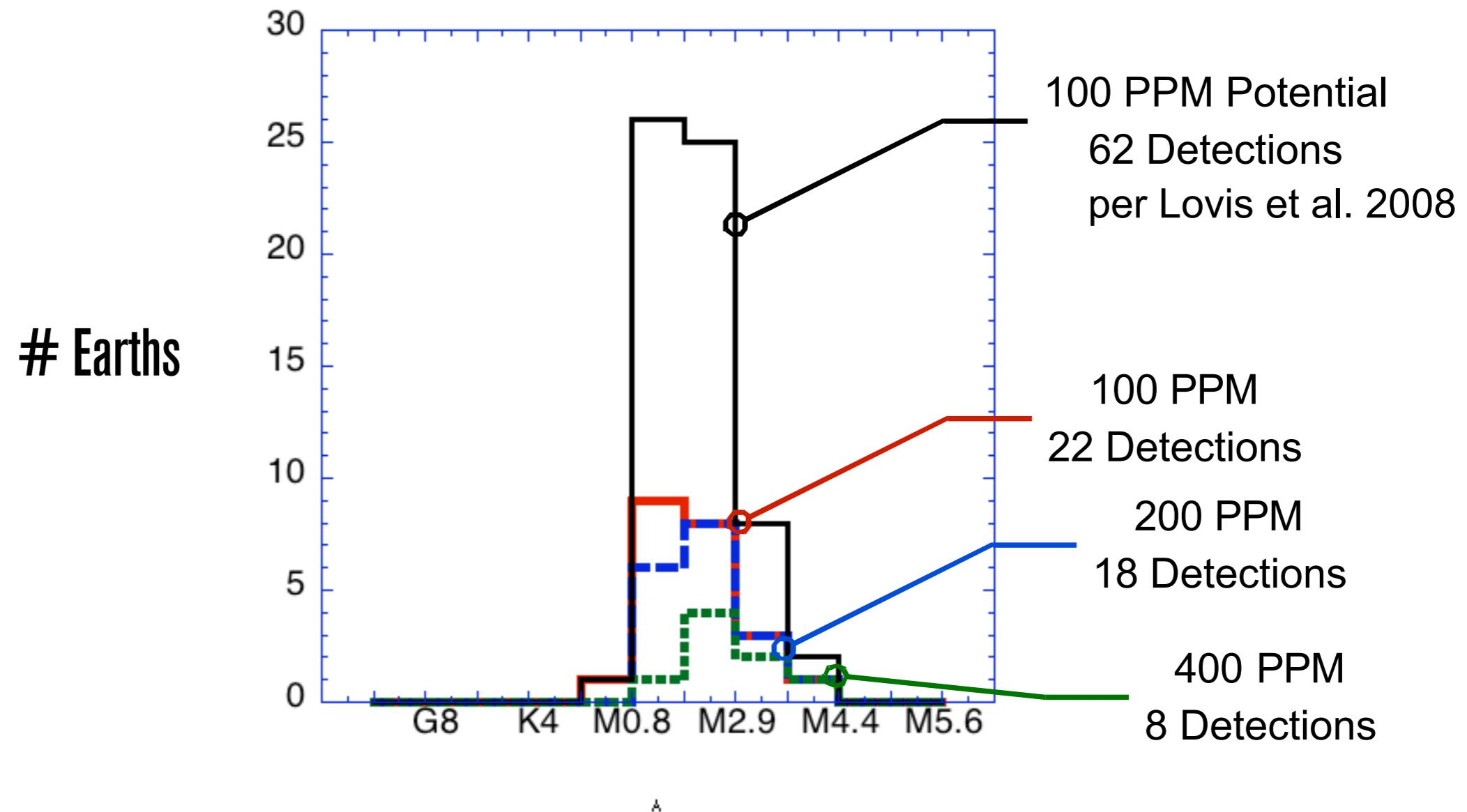
TESS-discovered Earths (baseline)



22 Estimated Earths at 100 ppm



Potential Yield of Earths

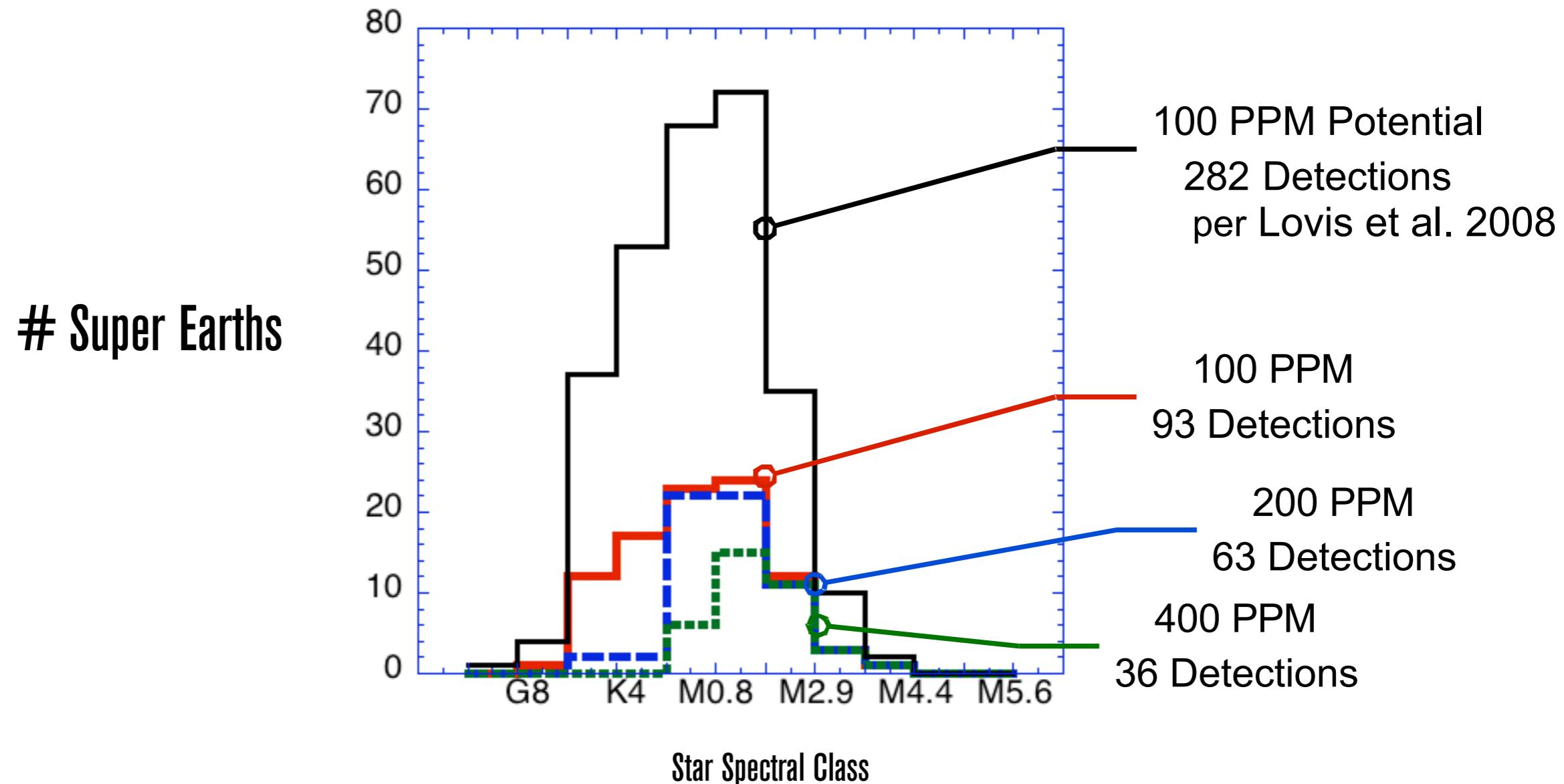


Estimated Yield of Earths Ranges from 22 to 62



Super Earths ($1.75 R_E < R < 3.5 R_E$)

100 ppm; CSR
200 ppm; CSR
400 ppm; CSR
100 ppm; Potential

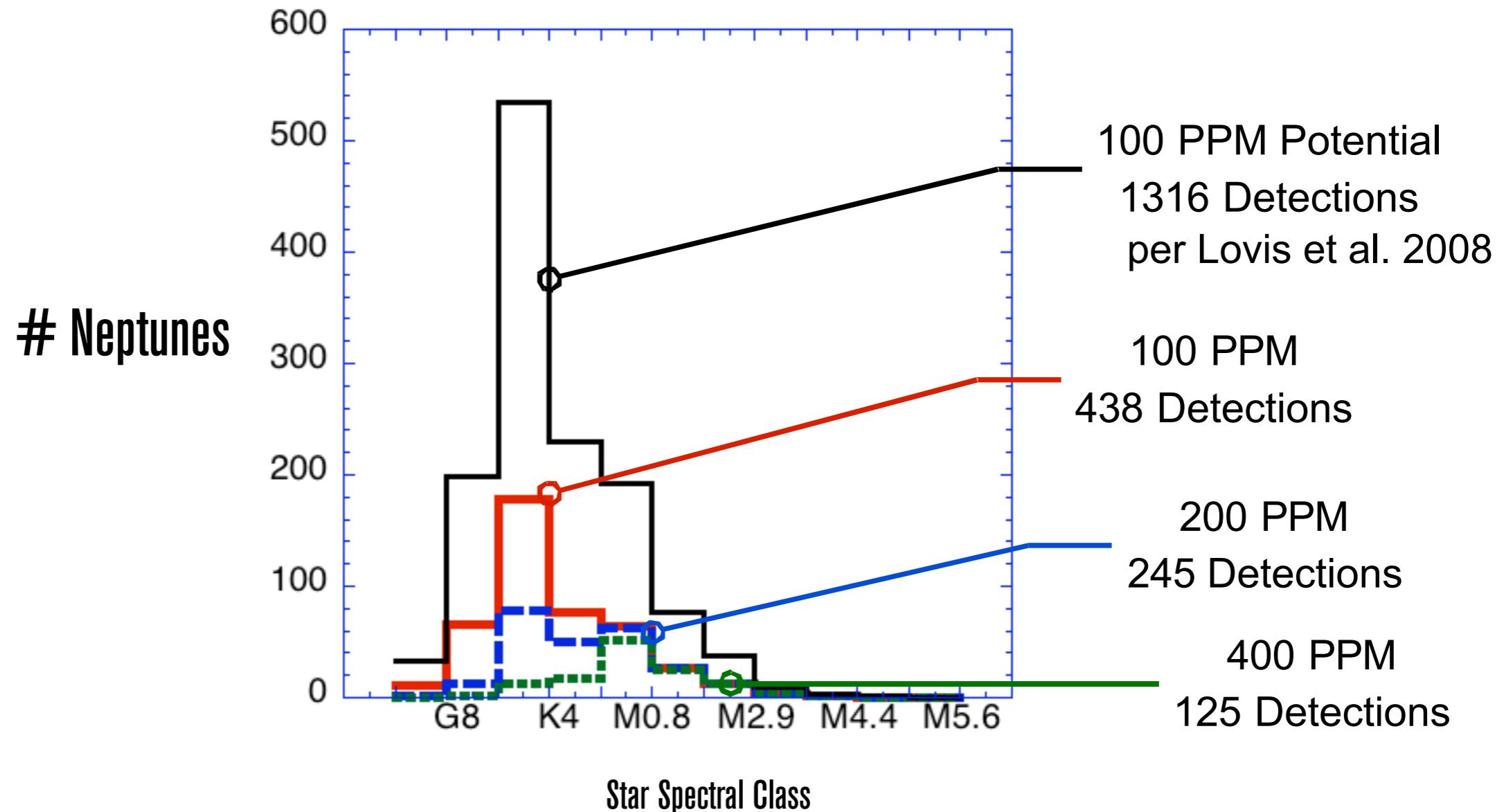


Estimated Super Earths Range from 93 to 282



Neptunes ($3.5 R_E < R < 6.5 R_E$)

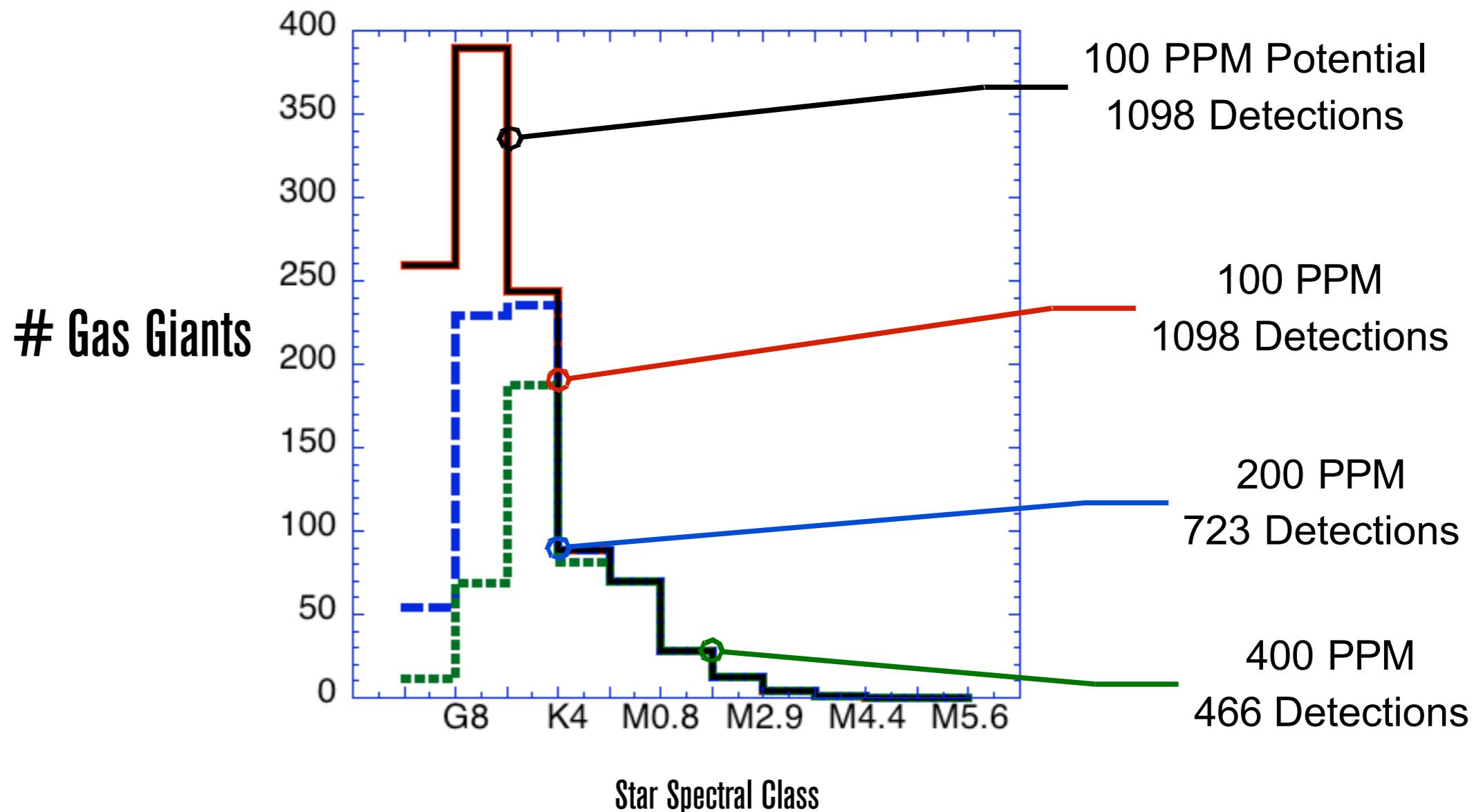
100 ppm; CSR
200 ppm; CSR
400 ppm; CSR
100 ppm; Potential





Gas Giants ($6.5 R_E < R < 13 R_E$)

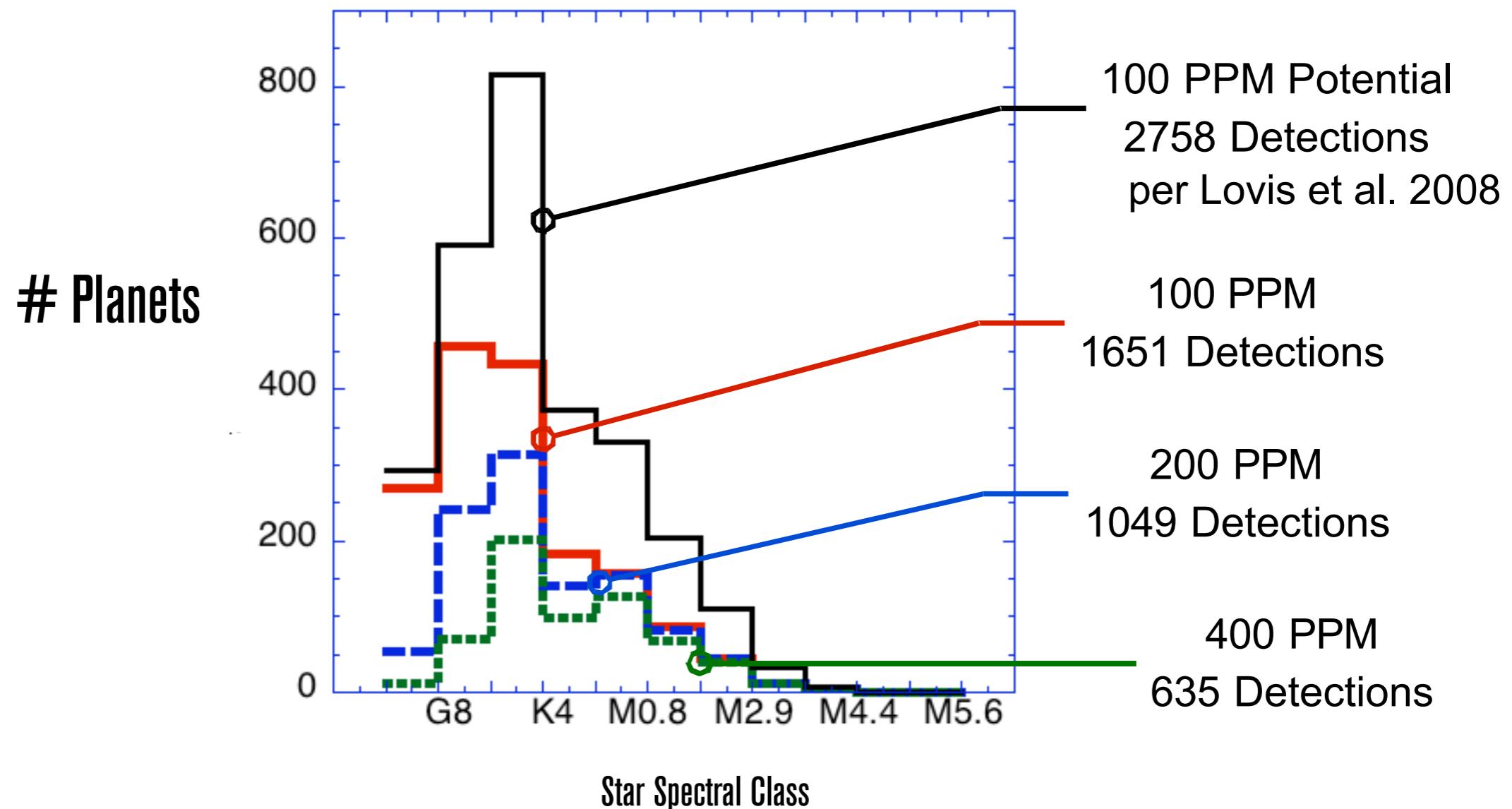
100 ppm; CSR
200 ppm; CSR
400 ppm; CSR
100 ppm; Potential



1098 Estimated Gas Giants (no impact from Lovis et al. 2008)



Total TESS Planet Yield



Estimated Total TESS Detections Range from 1651 to 2758



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Comparison of photometric precision for Kepler, CoRot, and TESS

Mission	Photometric Precision	Conditions	Reference
Kepler	17 ppm 19 ppm	V=+12.0; G2 star; 6.5 hr V=+8.0; G2 star; 600 s	Requirement: Kepler CDPP Program Document
CoRoT	63 ppm 35 ppm	R=+9; 512 s R=+8; 512 s	Measured in Orbit: Aigrain et al 2009 (astro-ph 0903.1829)
TESS	175 ppm 115 ppm	I=+8; 600 s I=+6; 600 s	TESS Specification

TESS Is Relatively Easy!





TESS Top Level Error Budget

Source	I=6 (e-)	I=6 (ppm)	I=8 (e-)	I=8 (ppm)
Shot Noise	17600	57	7015	143
Readout Noise	274	1	274	6
Dark Current	77	0	77	2
Sky Noise	850	3	850	17
Noise Floor (Margin)	23,289	75	3691	75
Other Sources (see Table 3.3)	19,346	62	3066	62
Total Noise	35,042	113	8,546	174
Total Noise (No Margin)	26,184	84	7,708	157

TESS Has 75PPM Additional Margin Against Future Noise Budget Growth





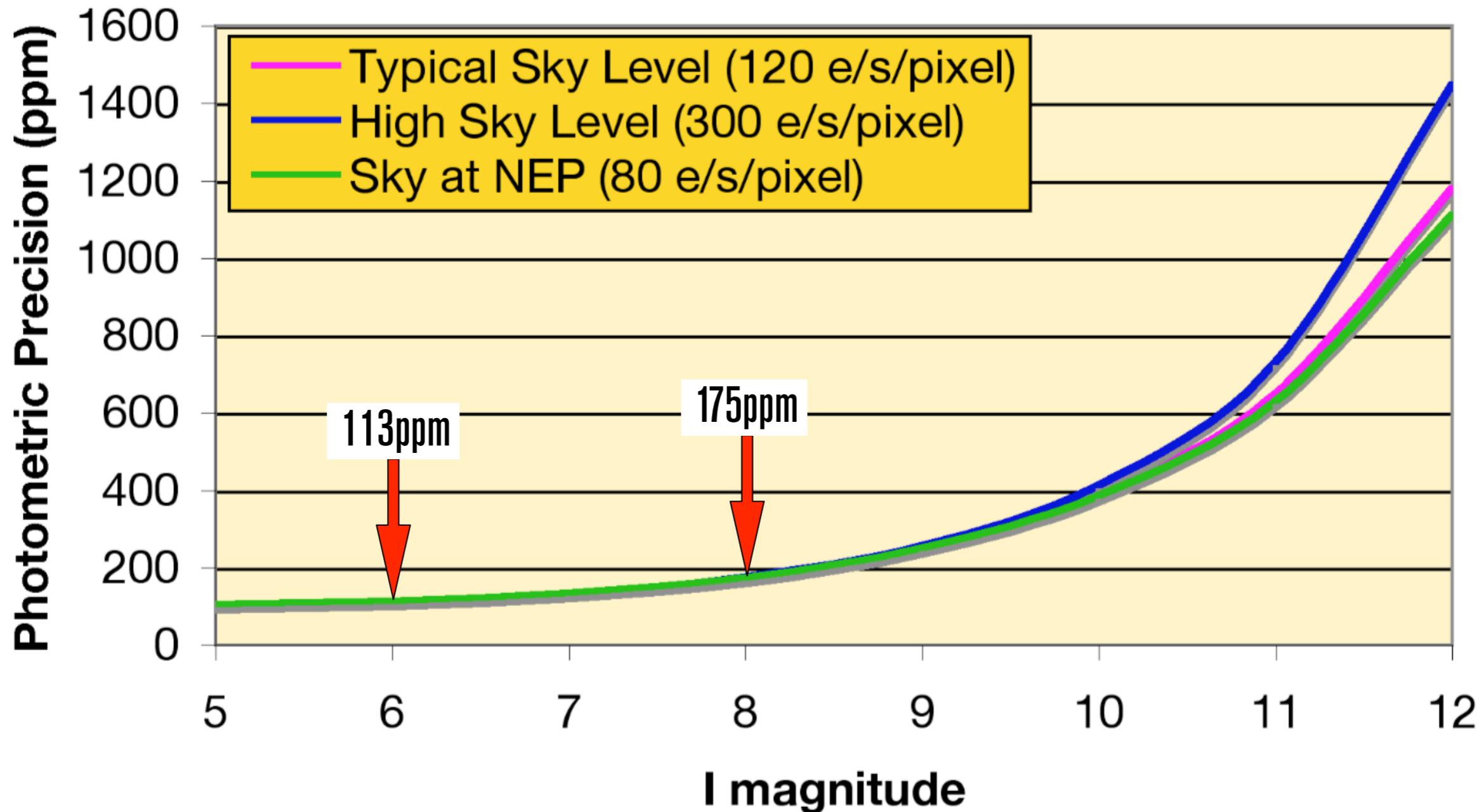
Noise/Error Source Table

Noise Term	Random or Systematic?	Timescale	Amplitude or Noise Level	Residual Noise (ppm)	Mitigation
S/C Motion	Random Systematic	0.03 Hz, 30 sec	3.5 arc-sec (3 sigma)	47	Averaging (Includes thermal motion; short term jitter) Detrend long term motion
Intra-Orbit DVA	Systematic	10 minutes	0-2 arc-sec	negligible	Repetition
Long-Term DVA	Systematic	36 days	0-8 arc-sec	negligible	Detrend
Other Long Term Shifts	Systematic	>>Transit time		negligible	Detrend
PSF Wings Changes	Systematic	10 minutes	$\leq 1^\circ\text{C} / \text{orbit}$	negligible	Repetition
Vignetting	Random	30 sec	<7 ppm	<<7	Averaging
Other Background	Random	Day/Weeks		negligible	Moon avoidance
Variable star confusion	Systematic			Not a Noise Term	Cotrending with position, centroiding to recognize location of variability
Flatfield variations	Systematic		None expected	negligible	Contamination Plan
Gain instability	Systematic	Minutes	0.2%/°C	negligible	Temperature Control Relative photometry
QE instability	Systematic	Minutes	<16 ppm	<16	Temperature Control Averaging
Bias instability	Systematic	Seconds	None expected	negligible	Correct with data
Stellar Variability Noise	Random	Orbit	37	37	Detrend
Noise Subtotal				62.3	





Photometric Precision vs. Stellar I Magnitude



“High Sky” level occurs close to the galactic or ecliptic planes.

“NEP” level is that found at the North Ecliptic Pole



TESS Photometric Precision

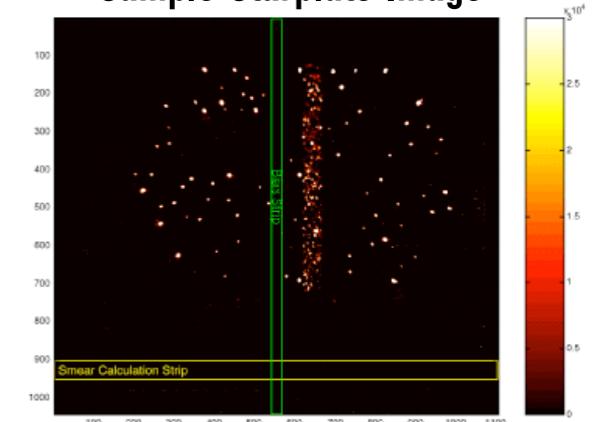
- TESS has a good handle on actual and potential noise/systematic error sources
 - “Bottoms Up” analyses of proposed hardware
 - Kepler expertise and heritage
- TESS will utilize the existing and facilities to better understand the list of noise/systematic error sources
 - Kepler Technology Demo (KTD) Hardware
 - End to End Test Model (ETEM) Software
- Early recognition of potential noise/error sources will enable timely trade studies
 - Kepler (2009-2012) and TESS (2013-2014) primary missions are well-phased

Kepler Tech Demo Testbed



TESS Carries 75 ppm Margin Against Future Noise Budget Growth

Sample Starplate Image



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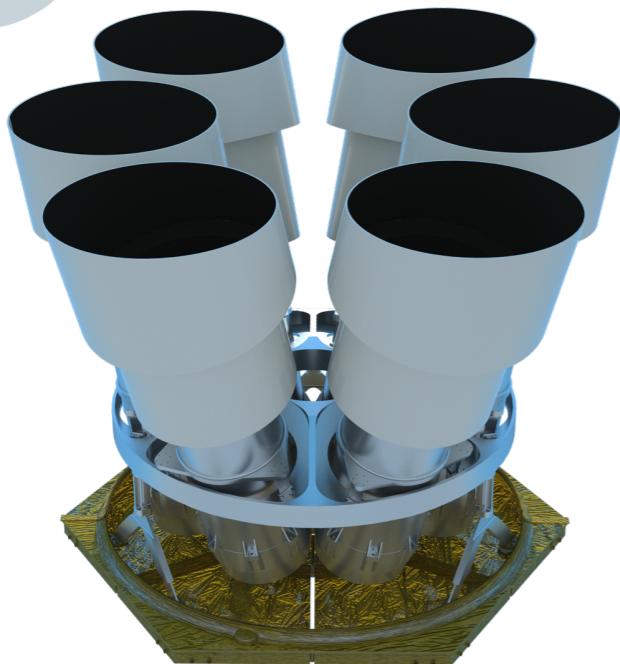


Outline

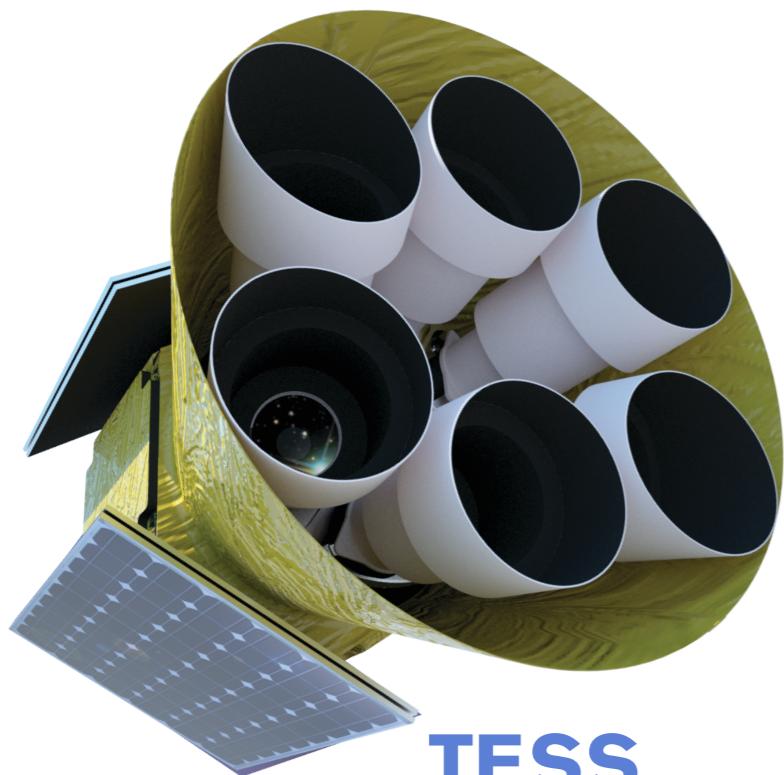
- Science Goals
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TESS Instrumentation



Six Camera Ass'y

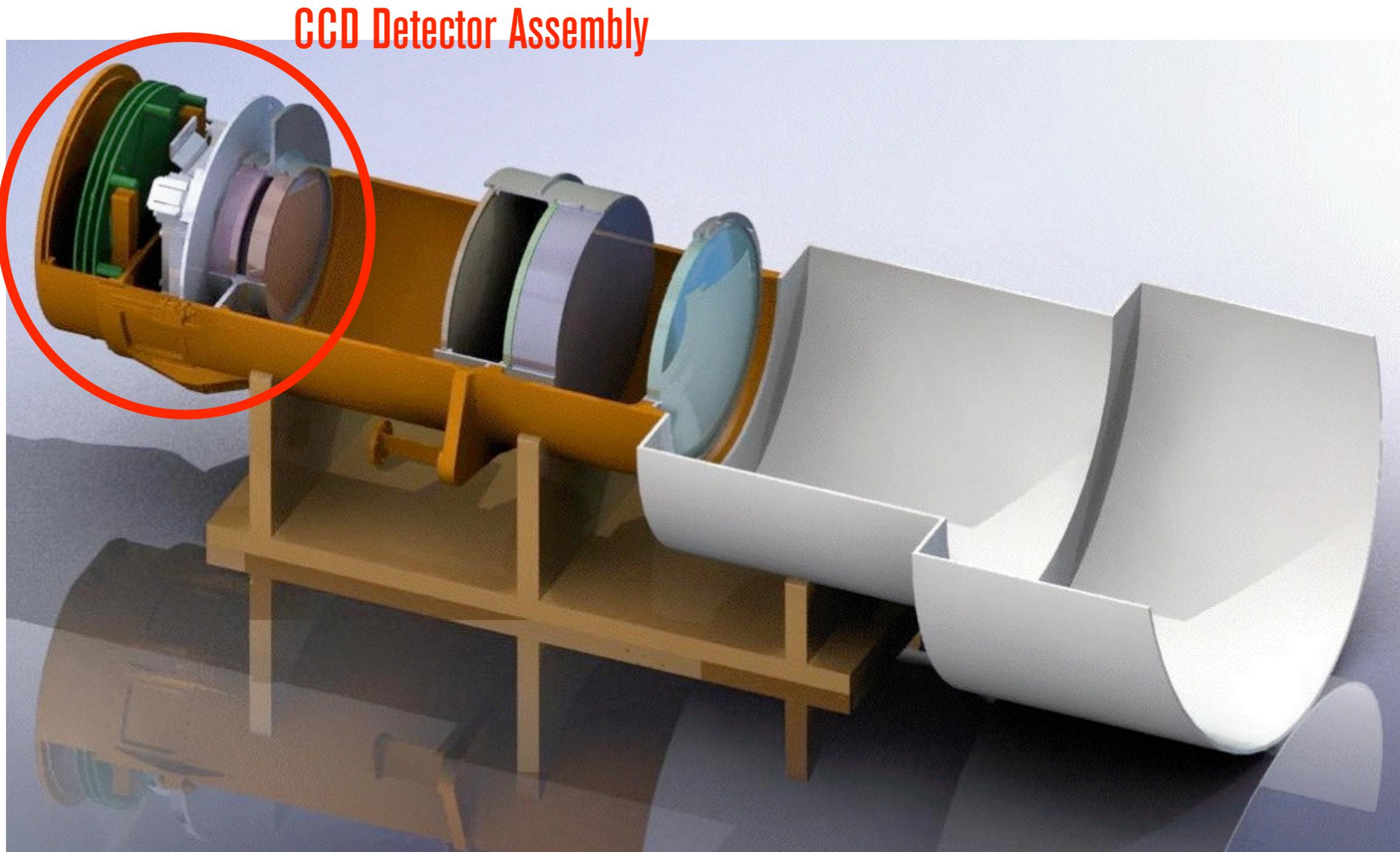


**TESS
“all-dressed up”**

TESS Characteristic	Value or Range
CCD Detectors	Quad MIT/LL CCID-68s (4000x4000 imaging array @ 15μm/pixel)
CCD Mode	Shutterless: 2 s integrate, 2 ms frame transfer
CCD Space Flight History	6 years operation on HETE-2 (as CCID-20) Very low hot pixel rate in equatorial orbit
Lens Aperture	12.7 cm
Pixel Scale	16.3" pixel ⁻¹
Camera Field-of-View	18° x 18°
Number of Cameras	6
Ensemble Field-of-View	54° x 36° = 1944 deg ²
Pass Band	600-1000 nm
Data Downlink Rate	10 Gbytes day ⁻¹
Launch Date	Late 2012
Survey Duration	2 years for All Sky



TESS Camera Assembly Cross Section



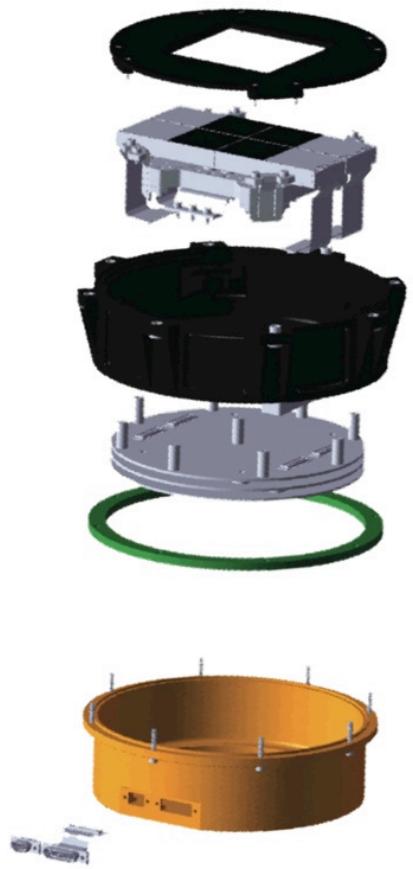
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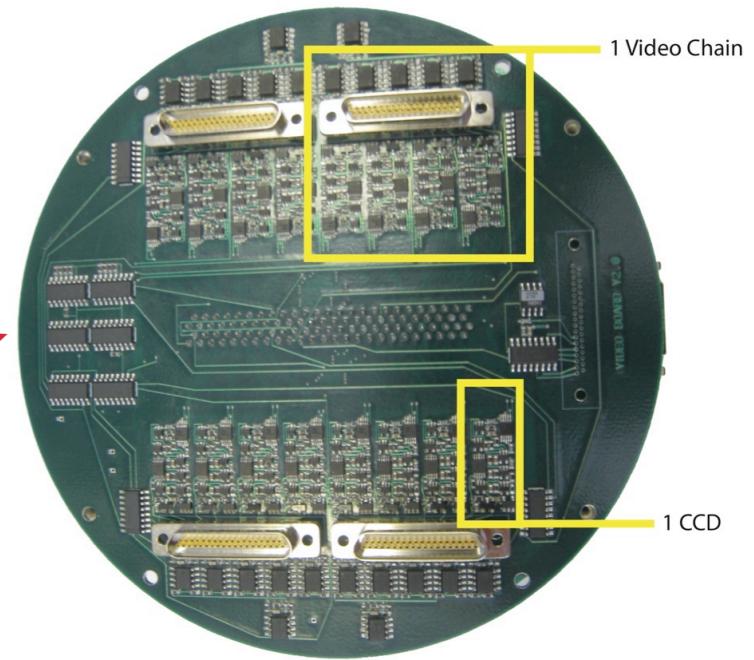


TESS CCD Focal Plane & Electronics Assembly

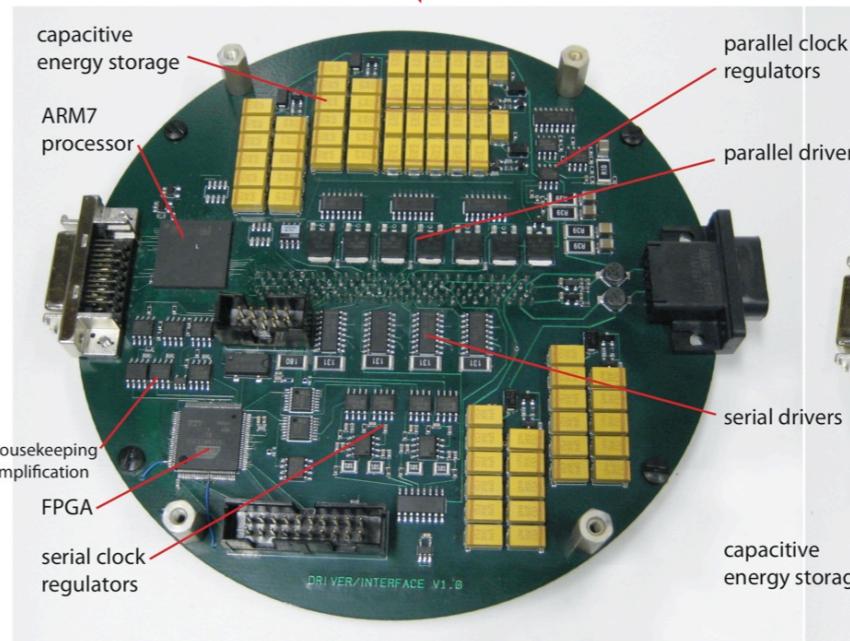
CCD Focal Plane (4 CCDs)



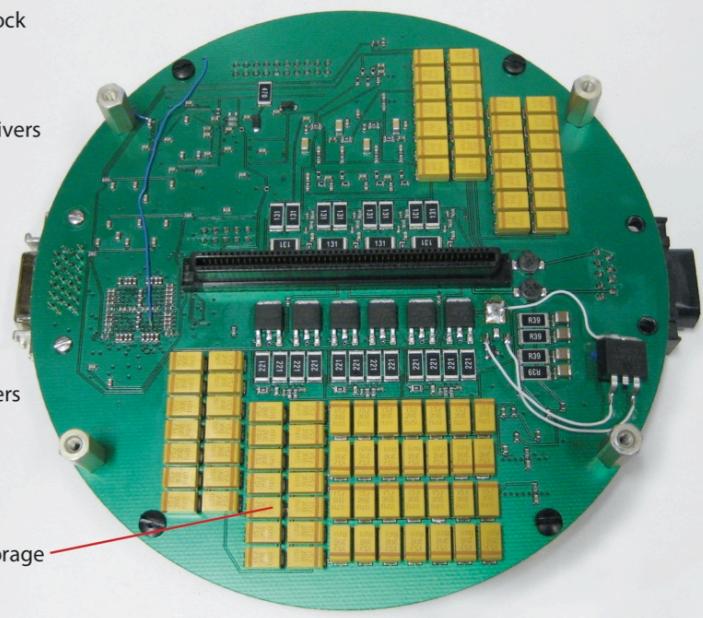
Video Board (16 Chains)



Clock Driver & Camera Link Interface Board



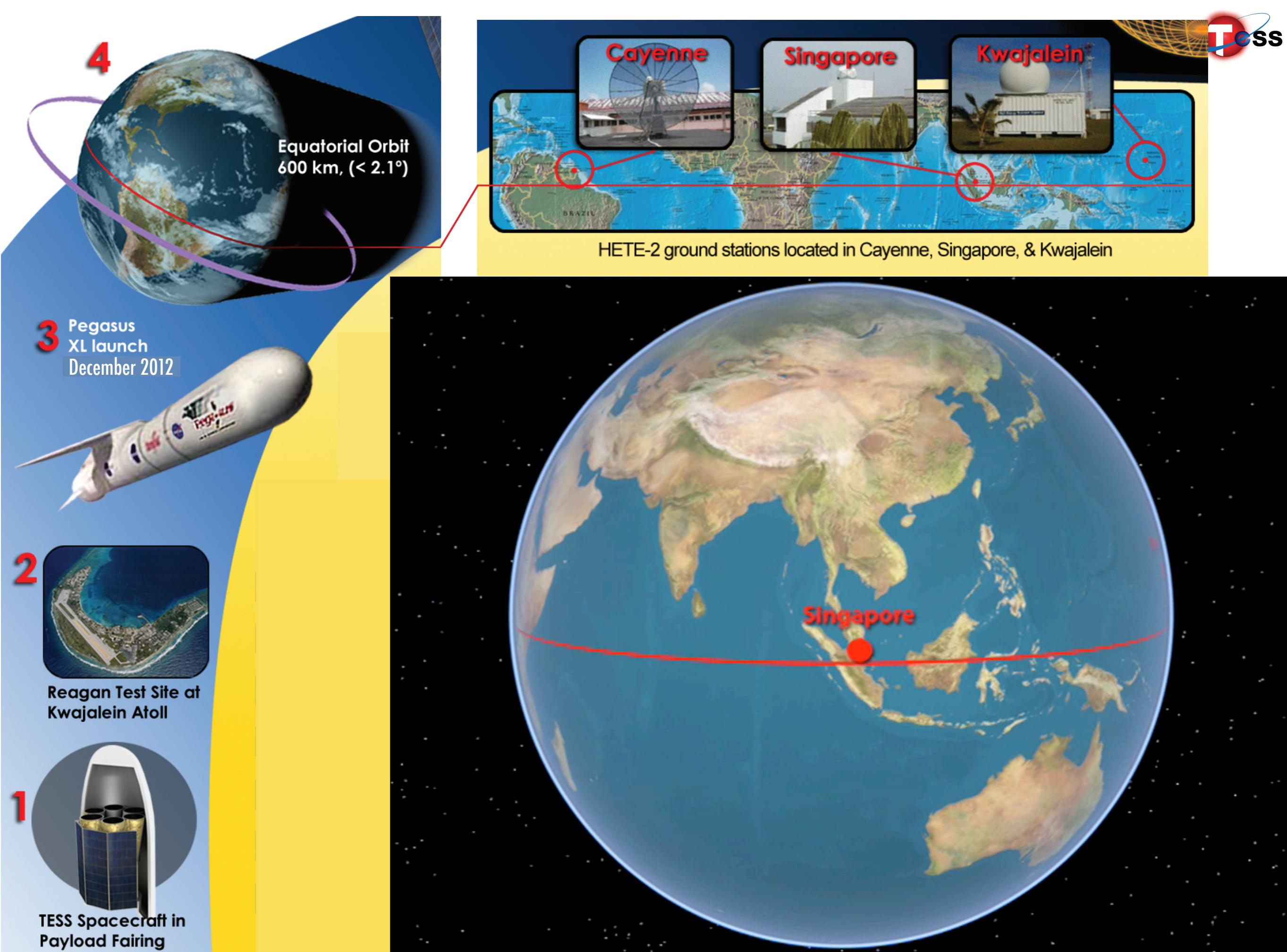
Top View



Bottom View



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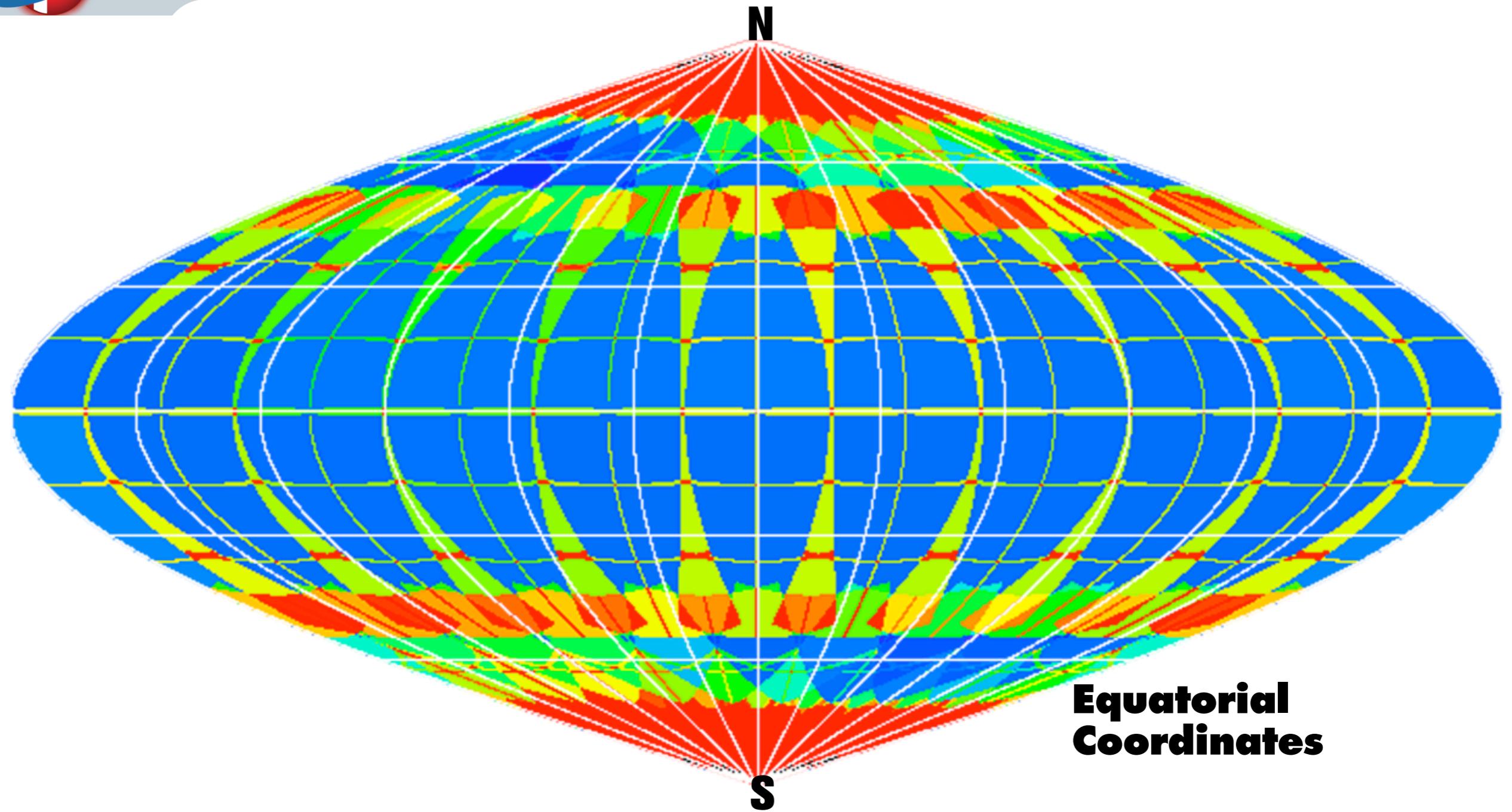


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TESS Sky Coverage in 2 yr Survey



1E+06 2E+06 3E+06 4E+06 5E+06

CODE: TIME OF EXPOSURE (IN SECONDS) IN A TWO YEAR MISSION



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TESS Ground Followup Program

◆ TESS: Establishes an Exoplanet Candidate List

(~ 10^4 sources from ~ 2×10^6 TESS survey candidates)

Candidates typically **10-20 x brighter**
than those for Kepler/CoRot

◆ Transit Confirmation by:

→ Radial Velocity Spectroscopy

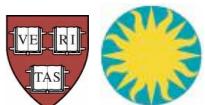
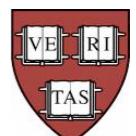
- ▶ “Low Precision” ~ 100 m s^{-1}
- ▶ “High Precision” ~ 1 m s^{-1}

→ Narrow Field Photometry

◆ Details given in

Brown & Latham 2009
(astro-ph:0812-1305)

CONTRIBUTORS



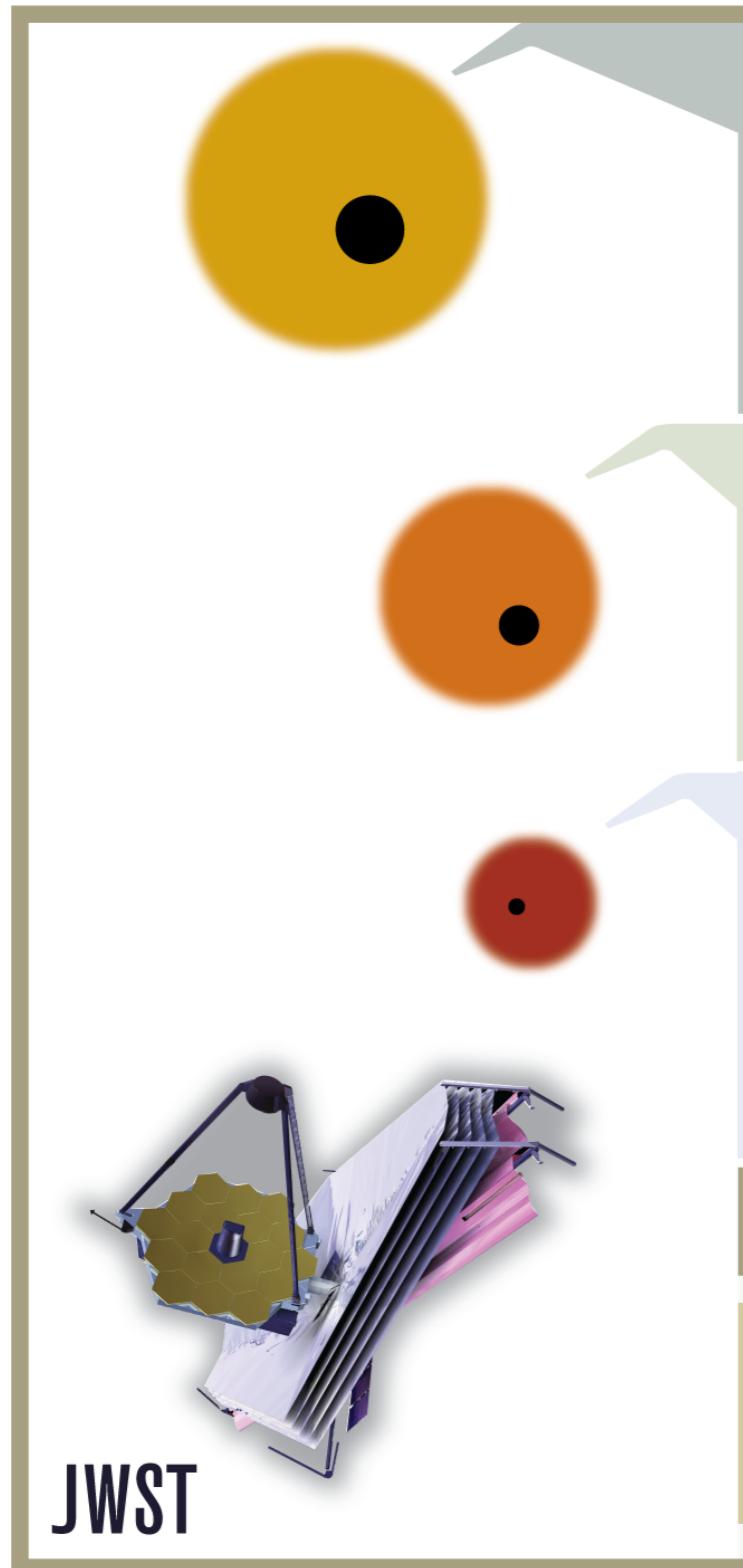
■ Harvard	■ SAO
■ Las Cumbres Observatory	■ Tokyo Inst of Tech
■ SUPAERO	■ Geneva Observatory

OBSERVING FACILITIES

LCOGT (1m x 18; 0.4m x 40)
FLWO (1.5m + TRES)
Euler (1m + Coralie)
Magellan (6.5m x 2)
HARPS-S HARPS-NEF HIRES



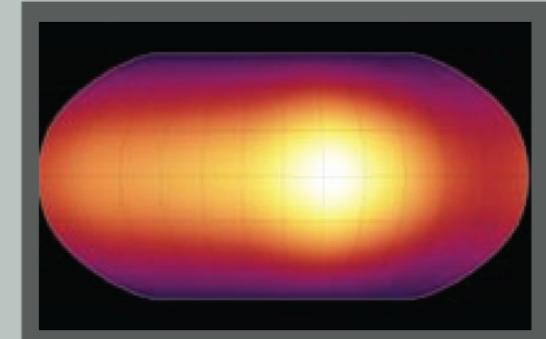
TESS Targets Enable Comparative Planetology with JWST



WEATHER ON HOT JUPITERS

1000+ TESS-provided sample

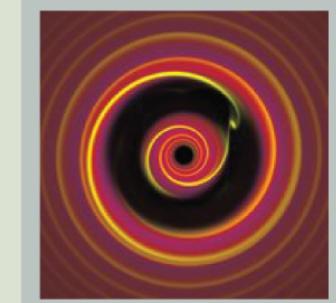
- Compare hot ($\sim 0.05\text{AU}$) and cooler (0.1-0.2AU) systems
- Determine radiation time scales
- Measure temperature with altitude



FORMATION AND MIGRATION OF NEPTUNES

700+ TESS-provided sample

- Evaluate gas fraction vs. remnant core
- Differentiate atmospheric composition based on migration models



WET SUPER EARTHS

100+ TESS-provided sample

- Compare hot Super Earths around late type K stars and cooler Super Earths around mid-late M stars
- Investigate signs of habitability



TESS & JWST

TESS provides WHERE to look

1. Star Location on sky

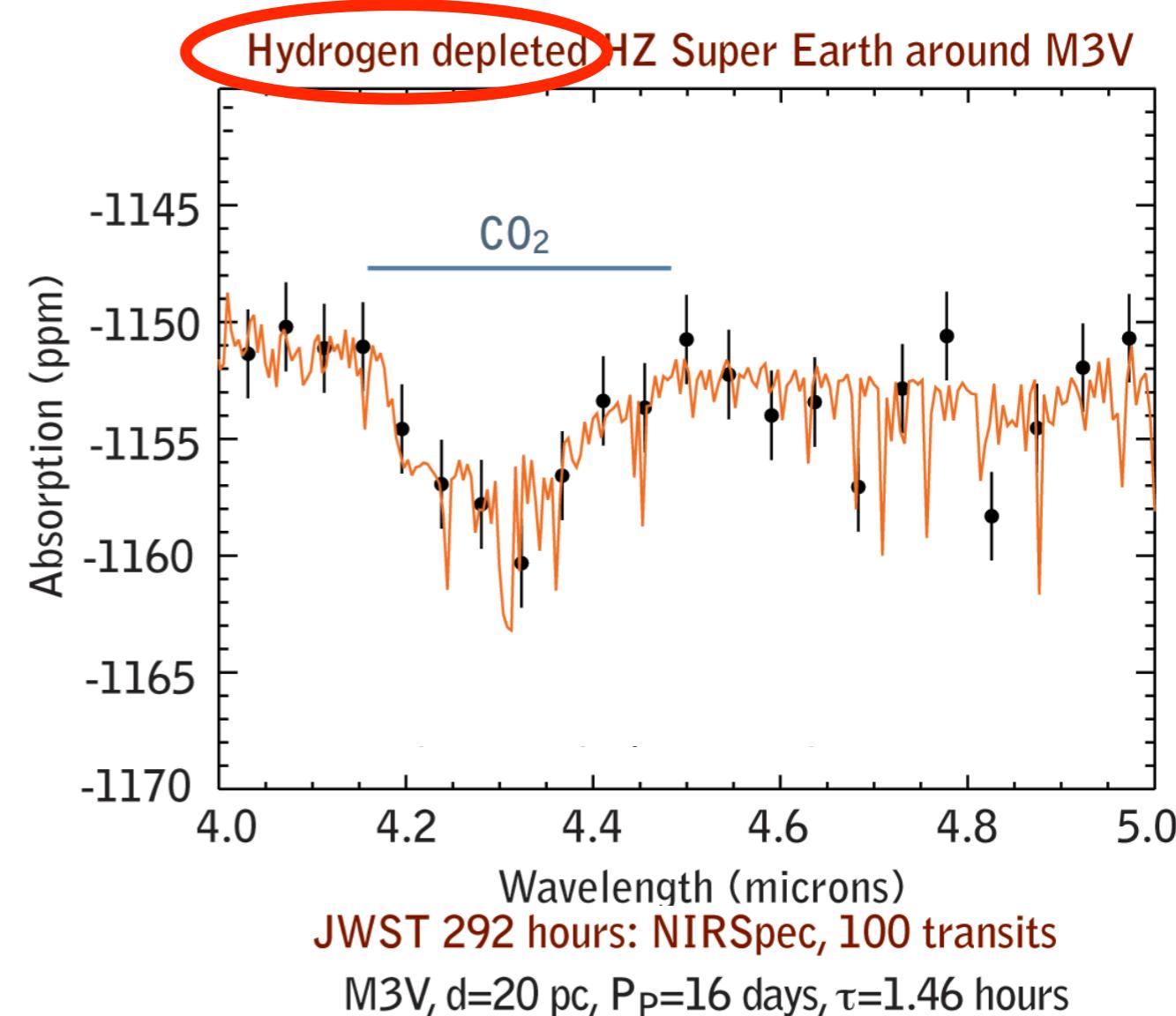
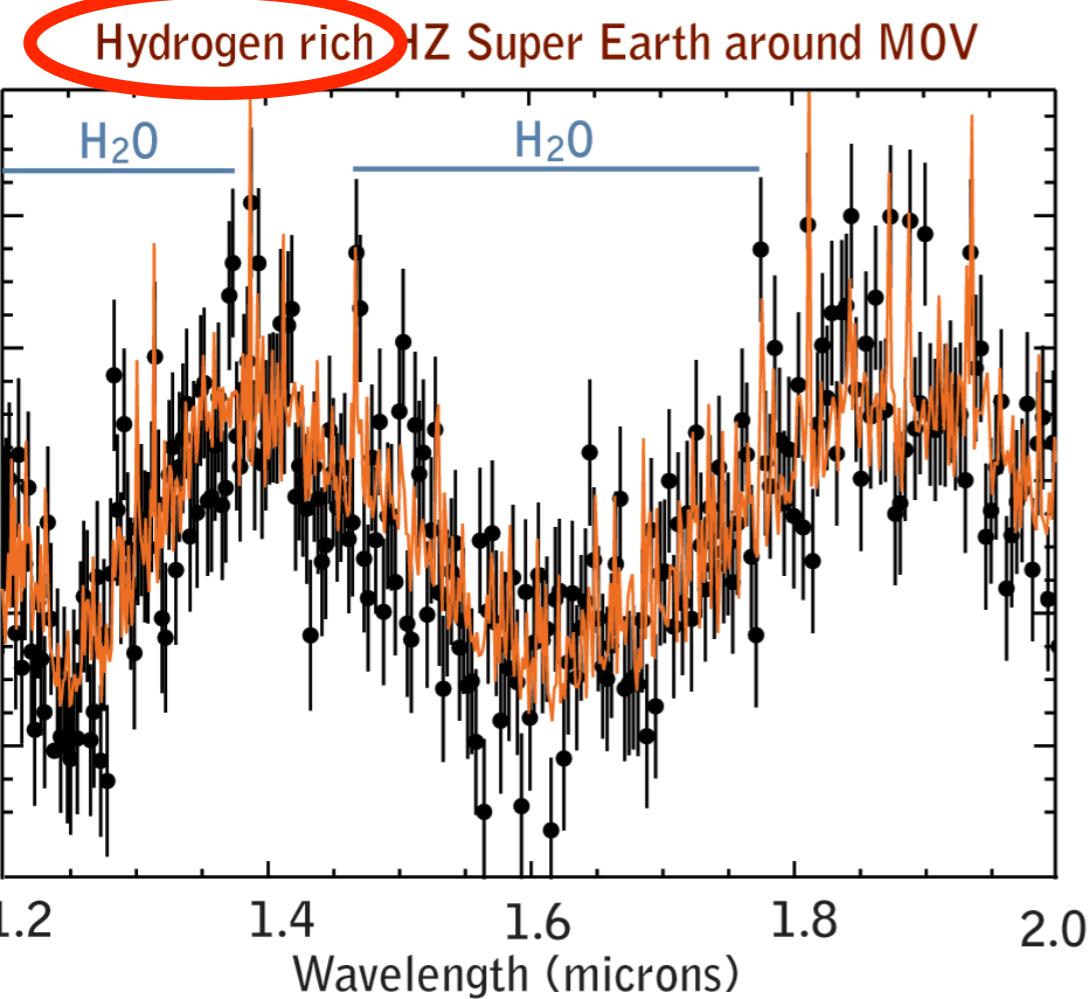
TESS provides HOW to look

2. Star Brightness

TESS provides WHEN to look

3. Planet Transit Time

TESS Finds the Best and Brightest Targets for JWST



Black Dots:

Examples of simulated NIRSpec/JWST spectra for two potentially-habitable TESS-discovered Super Earths orbiting late type stars

Orange Lines:

Model atmosphere spectra

(Miller-Ricci, Seager, & Sasselov 2009, ApJ, 690, 1056-1067)

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Deming et al. 2009
astro-ph: 0903.4880



Parameters used in JWST Simulations for TESS-discovered HZ Super Earths

Parameter	H-rich	H-depleted
Planet Temperature	300K	300K
S/N of atmospheric feature	>100 (H ₂ O at 1.6μm)	7 (CO ₂ at 4.3μm)
Composition	Solar	Intermediate (10% H, 40% H ₂ O, 40% CO ₂)
Surface Pressure	10 atm	1 atm
Scale Height	110 km	8 km
Radius*	1.8 R _{Earth}	1.8 R _{Earth}
Mass*	5 M _{Earth}	5 M _{Earth}
Descriptor	“Water Worlds”	
NIRSPEC Systematics	100 ppm for 10s (Lindler & Clampin)	

*GI 581c analog (Miller-Ricci, Seager, & Sasselov 2009, ApJ, 690, 1056-1067)

Deming et al. 2009
astro-ph: 0903.4880



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- **Low Cost SMEX Exoplanet Mapping Mission**
 - In Phase A now; down select in June
 - Launch in late 2012
 - Targets 2.5 million bright and nearby stars
 - All sky survey in 2 years (2013-2014)
 - Complements CoRot & Kepler “narrow-deep” surveys
- **Equatorial orbit**
 - Enables simple operations
 - Very low radiation orbit (no SAA)
 - Assures optimal CCD performance
- **No new technologies**
- **Extensive ground-based follow-up program**
- **Rich science yield:**
 - >100 earth-sized and super-earths orbiting bright stars
 - Bright, nearby targets for upcoming NASA missions
(JWST in 2014; upcoming Exoplanet Probes, Flagship missions ...)

